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RESEARCH

Is There a Synchronizing Influence of Planets on Solar and Stellar Cyclic Activity?

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Abstract
This work continues our research of the connection between the long-term activity of stars and their planets. We analyze new data on the previously considered two dozen solar-type stars with identified cycles, adding the results of studying the long-term variability of two more solar-type G stars and 15 cooler M dwarfs with planets. If the cyclic activity is determined by a strong tidal influence of the planet, then the cycle duration of the star should be synchronized with the period of orbital revolution of the planet. We calculate the gravitational effect of planets on their parent stars. The results obtained confirm the earlier conclusion that exoplanets do not influence the formation of the stellar cycle. We examine the change in the position of the barycenter of the solar system relative to the center of the Sun over 420 years. A comparison of these data with the most reliable 120-year SSN (sunspot number) series as the index of solar activity has shown that they are not synchronized.

Keywords Stellar cycles · Solar cycle · Exoplanets

1. Introduction

The cyclic magnetic activity of the Sun in the form of the Schwabe cycle is one of the most famous phenomena of solar physics driven by the solar dynamo. It is believed to be based on differential rotation and mirror-asymmetric motions in the solar convection zone.

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The point, however, is that the duration of this cycle (about 11 yrs) is close to the orbital period of Jupiter (also about 11 yrs). Solar physicists (e.g. Hazra et al. 2019; Reiners et al. 2022), including the members of our team, usually consider this fact to be just a coincidence; however, some are inclined to believe that Jupiter does contribute to the physical processes responsible for the cycle (e.g. Scafetta and Bianchini 2022; Klevs, Stefani, and Jouve 2023, and references therein). Indeed, it is quite difficult to prove that one physical phenomenon does not influence another, and there is no need to argue that planets cannot anyhow affect solar activity in principle.

The progress in present-day astronomy makes it possible to have a broader look at this old controversy. Indeed, cyclic activity is known to exist at dozens of stars more or less similar to the Sun, and some of them have exoplanetary systems confirmed by observations. This fact allows us to enlarge substantially the observational basis of the discussion. Obridko, Katsova, and Sokoloff (2022) carried out a corresponding analysis of observational data and found no evidence that stellar cycles could be considered a manifestation of planetary influence on the interior of the star. That article was the first step in this direction, but it did not cover all aspects of the problem. It still deserves a more systematic study, which is even more motivated taking into account the rapid progress in this field.

We appreciate that the planetary explanation of the solar cycle looks quite implausible in the context of contemporary solar physics, and one could say that the burden of proof lies with the proponents of the theory. However, taking into account that the topic under discussion is interesting and important for quite a broad audience, we believe that the arguments based on direct astronomical observations rather than on theoretical ideas could be important here.

This is the motivation of the present article. In particular, we analyze the latest data on the activity of the previously considered solar-type G and K stars and complement them with data on the long-term variability of 15 cooler M dwarfs with planets. We carry out a detailed analysis of the possible tidal influence of a planet on the parent star, including data on the barycenter position of the planetary system. We analyze the barycenter position of the solar system over 420 years and compare it with available sunspot data.

2. Observations of Stellar Activity Versus Planetary Data

2.1. Updating the Magnetic Cycle Data

First, we have updated the list of stars with known magnetic activity and the exoplanetary data used in our previous work (Obridko, Katsova, and Sokoloff 2022) based on the stellar activity data from Baliunas et al. (1995). This dataset is complemented with the latest data from Baum et al. (2022) to add stars that were not considered by Baliunas et al. (1995). Obviously, it is important to demonstrate that using Baum et al. (2022) as the preferred source of information, we arrive at the same conclusions. A comparison is made (Table 1) to show that for stars with known exoplanetary systems, the changes in the magnetic activity revealed by Baum et al. (2022) do not affect the conclusion about the lack of connection between the planets and stellar activity.

More precisely, Baum et al. (2022) slightly modified the cycle length estimates for particular stars; however, these changes are comparable with cycle-to-cycle variations in the length of the solar cycle. For HD 190406, the data accumulated allows us to draw a fairly definite conclusion about the type of stellar activity. For HD 166620, it is possible to show that the star shows a behavior similar to that of the Sun during the Maunder minimum.

Table 1 Comparison of the activity data for stars with planetary systems from Baliunas et al. (1995) and Baum et al. (2022). E means that the authors define the cycle as "Excellent", i.e., the most reliable (Baliunas et al. 1995). Baum et al. (2022) use this definition by default. MM indicates that we are presumably dealing with an event of the type of the Maunder minimum (Luhn et al. 2022). Here P_{cyc} is the length of the activity cycle.

Star	Baliunas et al. (1995)		Baum et al. (2022)	
	P_{cyc}, yrs	Activity type	P_{cyc}, yrs	Activity type
HD 4628	8.4	E	10.0	E
HD 10476	9.6	E	10.3	E
HD 26925	10.1	E	9.9	E
HD 166620	15.8	E	17.0	E, MM
HD 190406	3.6 + 16.9	fair + good	17.2	E
HD 152391	10.9	E	9.1	E
HD 219834	10.0	E	9.4	E

Both conclusions do not help us relate the phenomenon of the stellar cycle with planetary influence.

When compiling Table 1, we have ignored the suggestion of Baum et al. (2022) to separate naked-eye estimates of cycle length from cases where the data allow periodogram analysis. Obviously, the amount of data accumulated has enabled the use of more sophisticated processing techniques. However, historically, the discussion of planetary influences on the solar cycle began in the 19th century, based on data comparable in quality to modern data on stellar activity.

2.2. Exoplanets and Activity of M Dwarfs

In Obridko, Katsova, and Sokoloff (2022), we considered G and K solar-type stars with known cycles. The present analysis includes data on the magnetic activity of M dwarfs (Irving et al. 2023) hosting planetary systems (Table 2). The magnetic activity of M dwarfs seems to be a natural extension of the topic under discussion. Note that the data presented in Tables 2 and 3 are the result of long-term photometric monitoring, while the data considered above were obtained from the analysis of chromospheric activity. The interpretation of stellar activity in terms of the dynamo theory suggests that the physical processes responsible for magnetic activity on stars occur in the interior of the star, much lower than the photosphere, to say nothing of the chromosphere. However, it seems plausible to suggest that photospheric and chromospheric data represent the stellar activity. The current body of observational data appears to be insufficient to decide how important this difference is overall. In any case, we do not see any pronounced difference that is important in the context of the planetary hypothesis.

2.3. Additional Data Concerning G Stars

Further expansion of the observational database of our study is possible by including photometric data on stellar activity sufficient to identify the stellar activity cycle. Lehtinen et al. (2016) provided data on the magnetic activity of two G stars with confirmed planets, which are a useful addition to the data listed in Table 1 and the data used by Obridko, Katsova, and Sokoloff (2022) (Table 4).

Table 2 M dwarfs with planets and the type of activity known from Irving et al. (2023). P_{rot} is the rotation period, P_{cyc} is the cycle length, M_p is the mass of the planet (stands in the rows for planet), V_p (given in bold; see text for the definition) is the ratio of the planetary influence on the star to the influence of Jupiter on the Sun (stands in the stellar row), R_p is the radius of the planet, P_{orb} is the orbital period, and R_{orb} is the orbital radius in astronomical units (AU). The activity (stands in the stellar row) is denoted as follows: E stands for Excellent, G for Good, F for Flat, L for Long, P for poor, and V for Var (based on the probability of a false alarm). Me is the mass of the Earth, Re is the radius of the Earth, Mj is the mass of Jupiter, Rj is the radius of Jupiter, and * means that the orbital period is estimated by the Kepler law.

Name	P_{rot} d	P_{cyc} yrs	V_p or M_p	R_p	P_{orb}	R_{orb}
GJ 581* (M 3V)	141.6	3.8	**9186**			
GJ 581 b			15.9 Me	0.366 Rj	5.4 d	0.040
GJ 581 c			5.5 Me	2.21 Re	12.7 d	0.07
GJ 581 e			1.7 Me	1.17 Re	3.1 d	0.028
GJ 628 (M 3V)	79.6	3	**961**			G
Wolf 1061						
Wolf 1061 b			1.91 Me	1.21 Re	4.9 d	0.03
Wolf 1061 c			3.41 Me	1.66 Re	17.9 d	0.08
Wolf 1061 d			7.7 Me	0.24 Rj	217.2 d	0.04
GJ 849* (M 3.5V)	41.4	3.7	**3.37**			P
GJ 849 b			0.9 Mj	1.24 Rj	1914 d	2.35
GJ 849 c			0.702 Mj	1.25 Rj	7049 d	4.9
GJ 896A* (M 3.5V)	15.58	10.1	**638**			L
GJ 896A b			2.26 Mj	1.19 Rj	284.4 d	0.63
GJ 317* (M 3.5V)	57.5	2.3	**109**			L
GJ 317 b			1.7528 Mj	1.151 Rj	695.66 d	1.151
GJ 317 c			1.644 Mj	1.2 Rj	18.5 yrs	5.23
GJ 273 (M 3.5V)	115.9	5.8	**13**			G
GJ 273 b			0.0069 Mj	1.51 Re	18.64 d	0.09
GJ 273 c			1.18 Me	1.06 Me	4.7 d	0.036
GJ 273 d			0.0345 Mj	?	413.9 d	0.712
GJ 273 e			0.0297 Mj	?	542 d	0.849
GJ 447 (M 4V)	175.9	5.3	**156**			P
Ross 128						
Ross 128 b			1.11 Me	1.4 Re	9.9 d	0.049
GJ 54.1 (M 4V)	2.78	10.4	**1420**			G
YZ Cet						
YZ Cet b			0.913 Me	0.7 Re	2 d	0.016
YZ Ce tc			1.05 Me	1.14 Re	3.1 d	0.02
YZ Cet d			1.03 Me	1.09 Re	4.7 d	0.028

Table 2 (*Continued*)

Name	P_{rot} d	P_{cyc} yrs	V_p or M_p	R_p	P_{orb}	R_{orb}
GJ 551 (M 4.5V)	85.1	5	**7 x 10^5**			L
Prox Cen						
Prox Cen b			1.03 Me	1.07 Re	11.2 d	0.004
Prox Cen d			?	0.0008 Rj	5.167 d	0.028
GJ 406 (M 6V)	7.4	13	**1 x 10^5**			F
Wolf 359						
Wolf 359 b			0.138 Mj		2938 d	1.845
Wolf 359 c			0.012 Mj		2.687 d	0.018

Table 3 G stars with planets and the type of activity known from Lehtinen et al. (2016) (based on photometric data). Designations are the same as in Table 2. For comparison, we include the case of solar activity and Jupiter in the table.

Name	P_{rot} d	P_{cyc} yrs	V_p or M_p	R_p	P_{orb}	R_{orb} AU
HD 63433 (G5 V)	6.46	5	**5029**			P and L
V377 Gem						
HD 63433b			5.11 Me	2.112 Re	7.1 d	0.0714
HD 63433c			6.9 Me	0.225 Rj	20.5 d	1.1448
HD 63433d			1.25 Me	1.073 Re	4.2 d	0.0503
HD 70573 (G6 V)	3.31	6.9	**127**			G
V478 Hya						
HD 70573 b			6.1 Mj	1.14 Rj	2.3 yrs	1.76
The Sun	25 d	11 yrs	**1**			E
Jupiter			1 Mj	1 Rj	11.86 yrs	5.2

2.4. Stars with Cyclic Activity Without Planets

The observational base of our research can also be expanded by including stars with an established type of magnetic activity, for which the search for a planetary system was not successful (Table 4). We understand that the available planet detection method may fail to detect an existing planet. However, we believe that such an option should be taken into account. Indeed, if there are stars without planets but with a pronounced magnetic cycle, it becomes problematic to insist that the cycle as a physical phenomenon is associated with planets. In Table 4, we see at least one example (GJ 285) confirming this point of view. Let us note here that in modern scientific literature, it is not easy to identify cases of unsuccessful attempts to find exoplanets near a star. Perhaps by paying more attention to this search, the table could be expanded.

2.5. Summarizing New Observations

By summing up the data mentioned above (17 star systems) and the data used in Obridko, Katsova, and Sokoloff (2022) (15 star systems and the solar system), we actually double the

Table 4 Red dwarf stars with the type of magnetic activity, known from Irving et al. (2023), without a planetary system revealed by available observations. Designations are the same as in Table 1.

Name	$P_{\rm rot}$	P_c	Activity type
GJ 358 (M 4V)	25.2 d	4.7 yrs	P
GJ 729 (M 3.5V)	2.9 d	3.5 yrs	F
LP 816-00 (M 4V)	86.3 d	2.0 yrs	F
GJ 285 = YZ CMi (M 4V)	2.78 d	10.4 yrs	G
GJ 234 = Ross 614 (M 4.5V)	1.58 d	5.9 yrs	F

number of cases under consideration, although the resulting database becomes less homogeneous than in the latter mentioned article.

A preliminary analysis of the complete list reveals the following points. First of all, not all of the listed stars (33 cases) display a pronounced magnetic cycle, designated in the tables as G and E (10 cases). The above proportion can hardly be considered a correct estimate of the share of stars with pronounced cycles among all candidate stars with periodic activity. However, we believe that this relationship can be used as an approximation. Apparently, there is something else to take into account, i.e., the rotation of the star. This condition is entirely consistent with the dynamo interpretation of activity cycles and seems problematic in terms of the planetary hypothesis.

The parameters of stars and planets are taken from the Exoplanet Search Catalogues, a link to which is provided in the Data Availability declaration.

The tables do not provide clear support for the planetary hypothesis. Perhaps we can take a closer look at the following cases.

Case HD 176051AB (G0 V), i.e., Jupiter at the orbit of Mars, seems most promising. According to the planetary hypothesis, one would expect a cycle length of about 3 years, while the actual cycle is about 10 years, and observers do not consider these numbers to be particularly reliable.

Case GJ 628 (dM3), i.e., the Earth inside the orbit of Mercury, and case GJ 896A (dM3.5), i.e., Jupiter at the orbit of Venus, give an activity cycle several times longer than the orbital period. Case GJ 273 (dM3.5) involves many planets and opens the way to various speculations. However, it does not allow us to simply identify the duration of the activity cycle with the revolution period. In two out of three cases, we have the periodicity of type G.

As regards the interpretation in terms of the planetary hypothesis, we estimate the tidal effect V_P caused by the gravity of planetary systems and compare it with the effect arising from the influence of Jupiter on the Sun (see Tables 2 and 3). The quantity V_P is estimated as the ratio $Mr^2(3\cos^2\phi - 1)/R^3$ calculated for a given planetary system and is related to the corresponding quantity in the solar system. The scaling can be found in various textbooks; see, e.g., Murray and Dermott (1999). Here, r is the stellar radius, M is the planetary mass, R is the orbital radius, and ϕ is the angle between the orbital plane and the stellar equator. Note that the tidal potential on the surface does not depend on the mass of the star. If a star has several planets, we give the estimate for the planet with the maximum gravitation potential.

Analysis of the data obtained and their comparison with the data provided in Obridko, Katsova, and Sokoloff (2022) confirms that the gravitational effect V_p varies in a wide range and there is no clear connection between V_p and the properties of activity cycles of the parent stars. The only more or less clear message is that Jupiter's influence on the hydrodynamics of its parent star (the Sun) is, perhaps, not the largest on the list.

To summarize the above, we can say that we have made every effort to find any confirmation of the planetary hypothesis in the available observational data but have failed. Therefore, we have to consider the fact that the solar magnetic activity cycle is close to the orbital period of Jupiter as a simple coincidence, at least until some radically new data arrive.

3. Planets and Details of the Solar Cycle History

In this section, we will compare the characteristics of solar activity with the total influence of the planets determined not only by Jupiter. Note an important difference between the solar cycle and the barycenter motion: the latter is much more stable than the solar cycle. Indeed, the length of the solar cycle has varied by a year or two (sometimes more) during the history of instrumental observations of the Sun (about four centuries). For the same period, the cycle amplitude has varied much more substantially, at least by an order of magnitude, from the Maunder minimum at the middle of the 17th and the beginning of the 18th century to very high cycles in the second half of the 20th century. In principle, this approach provides many more opportunities for relating some features in solar cycle variations with planetary effects. The problem is to isolate a specific feature, associate it with another feature in the planetary motion, and propose a physical mechanism for this connection. We are not discussing any specific hypothesis with a developed physical mechanism here. There are many assumptions that more or less convincingly connect the dynamics of the solar cycle with the planetary motion (e.g. Jose 1965; Zaqarashvili 1997; Cionco and Pavlov 2018; Okhlopkov 2020). In particular, we agree with the idea proposed in the works cited above that the position of the barycenter of the solar system inside or outside the Sun is decisive for the shape of the cycle.

Of course, if Jupiter's orbital period is close to the duration of the solar cycle, the barycenter motion and, say, the sunspot number record does demonstrate similar features. Our point, however, is that both quantities display something more complicated than just a harmonic oscillation. Then, it seems reasonable to compare the phase behavior of both tracers (namely, the distance between the solar center and barycenter of the solar system and the sunspot number (SSN), see Figure 1). The barycenter distance is calculated based on Folkner et al. (2014). Here, we do not see any pronounced phase relationship between the two signals.

More precisely, the idea could be formulated as an assumption (e.g. Okhlopkov 2020) that during such outstanding events in the history of solar activity as the Maunder minimum, the barycenter was located in some special way (for example, inside the Sun). In order to verify this assumption, we present in Figure 2 the evolution of the solar system barycenter in the solar equatorial plane for two different epochs in the evolution of solar activity – the Maunder minimum (left panel) and the contemporary epoch (right panel). The equatorial cross-section of the Sun is shown as a red circle.

Strictly speaking, the time boundaries of the Maunder minimum are quite arbitrary. In Figure 2a, we choose 1645–1710 as the conditional time boundaries. The starting point is shown with a vertical red arrow; the points mark is made yearly. In Figure 2b, the points correspond to the period of Solar Cycles 21 – 24 (1976 – 2019); the first point is also shown with a vertical red arrow.

Of course, the trajectories differ; however, it seems difficult to choose which is more favorable to drive the solar cycle, since the sunspot statistics for both epochs is very different. A comparison of Figures 2a and 2b shows that there is no reason to assert that Maunder-type grand minima arise as the barycenter moves away from the Sun.

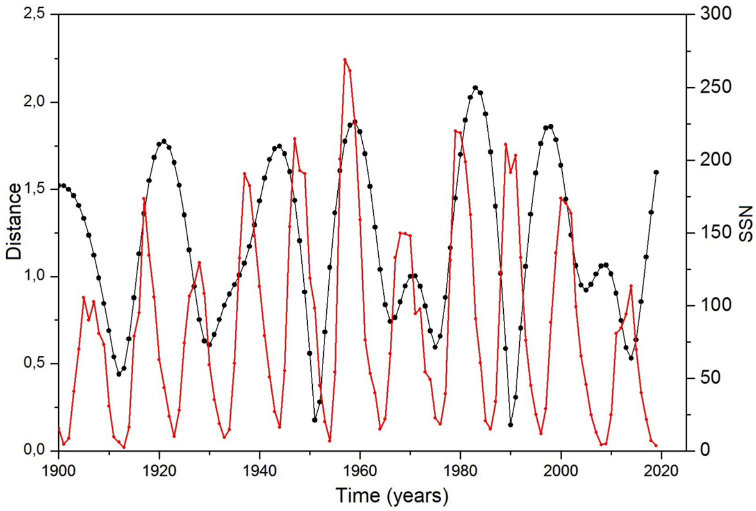

Figure 1 Evolution of the barycenter of the solar system (the distance from the solar center, black) and the sunspot number (SSN, red) from 1900.

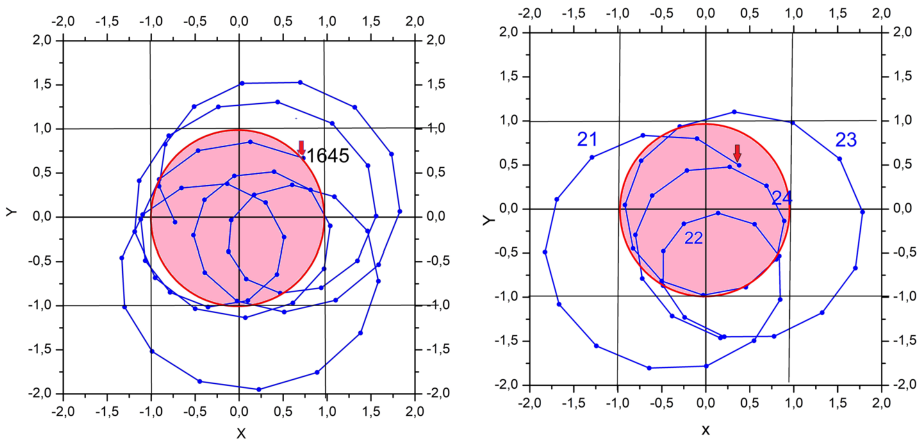

Figure 2 The motion of the solar system barycenter in the solar equatorial plane during the Maunder minimum (left, the starting point, 1645, is marked) and several recent solar cycles (right, cycle numbers are indicated). The solar interior is shown as a red circle. The x axis is directed from the Sun to the Earth.

Again, we agree that barycenter distance as an important participant in the excitation of the solar cycle looks quite implausible in the context of celestial mechanics (corresponding argumentation can be found in, e.g., Shirley (2006)). However, it might be helpful to support this theoretical argumentation by the fact that the behavior of the barycenter anticipated by supporters of the theory does not follow from the celestial mechanics equations.

4. Conclusion and Discussion

To summarize, we find no reason to consider the planetary effect as the main driving force of the solar magnetic cycle. In this sense, we confirm the earlier conclusion made in Obridko, Katsova, and Sokoloff (2022) and expand the observational base for this conclusion. In particular, in addition to stars with a magnetic periodicity different from the planetary orbital period, we present an example of a star with a magnetic cycle, which, however, does not have a planetary system (at least the search for exoplanets did not find any).

The main point is that the planetary hypothesis does not propose any clear mechanism independent of the stellar dynamo that would convert the mechanical force of the planetary motion into magnetic field variations.

We do not deny that planets may somehow affect the stellar activity cycle driven by motions unrelated directly to planetary effects. Again, we support our earlier conclusions (Obridko, Katsova, and Sokoloff 2022) and note a shift in part of some followers of the planetary hypothesis in this more fruitful (as we believe) direction (e.g. Stefani, Stepanov, and Weier 2021; Klevs, Stefani, and Jouve 2023). Indeed, having oscillations with two close periods of about 11 years, one can easily obtain beatings with a period of about 100 years (e.g. Stefani, Stepanov, and Weier 2021), which could be associated with well-known Gleissberg cycle (e.g. Hathaway 2010). However, the available bulk of observational data does not provide unambiguous confirmation of this idea. On the one hand, observers propose candidate stellar events similar to the Maunder minimum (e.g. Luhn et al. 2022) where long-term beatings are unlikely to be associated with the relationship between the cycle length and the orbital period. On the other, the behavior of the solar activity reconstructed for 10,000 years based on isotopic data (see, for review, Usoskin 2023) demonstrates a number of the Maunder-type grand minima, whose distribution on the time axis looks random rather than periodic as one could expect after a straightforward application of the idea of beatings. We certainly do not deny the existence of long cycles such as the Suess cycle. It is just that contemporary data are not enough to confidently detect them and establish a quantitative range of periods. At the present-day level of knowledge, it seems reasonable to avoid strong statements and consider the planetary effect to be a possible factor in the physics underlying the behavior of the long-term stellar cycle.

One more point to mention here is that the data concerning exoplanetary systems is biased by various selection effects. Further progress in exoplanetary studies hopefully should allow us to take selection effects into account and may, in particular, support (or reject) our conclusions.

Of course, the selective effect cannot be completely excluded. However, the observation conditions are such that it is selection that leads to the discovery of the most massive and (or) closest to the star planets. Additionally, these planets should make the most significant contribution to the potential.

Of course, we are aware that although qualitatively, both the tidal effect and the detection probability increase the mass of the planet (M) and decrease with the orbital radius (R), the quantitative dependence varies. The tidal effect scales as M/R^3 while, e.g., the radial velocity amplitude caused by a planet scales as $M^{3/2}/R^{1/2}$, the brightness of the planet for direct detection scales as $M^{2/3}/R^2$, etc. So, for a given sensitivity threshold, the allowed area in the M-R plane will be different for each of these.

Our selection includes exoplanets in a very wide range of masses, sizes, and distances. It is difficult to imagine that such a set arose as a result of selection.

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Author contributions Authors closely collaborated with the text. V.O. contributed mainly for solar activity aspects, M.K. and D.S. contributed mainly in stellar activity aspects and N.E. contributed mainly in celestial mechanics aspects.

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Data Availability The data on sunspots were taken from WDC-SILSO, Royal Observatory of Belgium, Brussels https://sidc.be/SILSO/datafiles. Search for exoplanets around stars was carried out in databases of NASA Exoplanet Archive https://exoplanets.nasa.gov/discovery/exoplanet-catalog/ and Extrasolar planet catalogues http://exoplanet.eu/catalog/. We used stellar activity data from Baliunas et al. (1995), Lehtinen et al. (2016), Baum et al. (2022), Irving et al. (2023). In this research, we used the SIMBAD database, operated at CDS, Strasbourg, France, and NASA's Astrophysics Data System Bibliographic Services.

Declarations

Competing interests The authors declare no competing interests.

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